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A Framework for Earthquake Risk Engineering

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Abstract

Catastrophe risk engineering (CRE) is the field of engineering that quantifies the risk of individual assets exposed to natural catastrophes, such as earthquakes or hurricanes, for the purpose of finding risk management solutions. An accurate estimation of the risk is essential for decision makers, such as risk managers or insurance brokers, who seek to either reduce or transfer the risk of the high-valuable assets in their portfolios.

Current practices in CRE use either oversimplifications of the structural systems and/or perform incremental dynamic analyses on limited number of ground motion records for the analyses selected by arbitrary heuristic methods. This paper proposes a novel framework for earthquake CRE. An accurate assessment of the earthquake risk requires a detailed analysis of the structural performance under site-specific seismic loading. Dynamic analyses of structures may be computationally expensive for complex structures, which are often overcome by simplifying assumptions at the expense of accuracy and rigor. The proposed framework uses a set of simulated ground-motion records consistent with the local-site seismicity. An efficient method based on stochastic reduced-order models is then used for running detailed dynamic analyses for the structural system.

The methodology proposed is validated for linear and non-linear systems located in a highly-seismic zone. Comparisons between the newly proposed and the traditional CRE frameworks are conducted.

Keywords: earthquake engineering, performance-based engineering, dynamic analysis, catastrophe-risk engineering

1. Introduction

Catastrophe risk engineering (CRE) is a branch of civil engineering that quantifies the risk of individual assets from a broad range of industries to catastrophic events such as low-frequency, high-impact earthquakes or hurricanes, in terms of physical damage and monetary loss [1]. CRE practice is used by decision-makers and risk managers to help them identify appropriate risk mitigation and management solutions, and to develop emergency response and recovery plans for assets in case of disasters. CRE requires a detailed life-cycle analysis of the asset in order to provide an accurate view of the structural performance, which is necessary for quantifying the risk of the asset exposed to the catastrophe. In the insurance industry, the catastrophe risk is usually quantified through metrics such as life-cycle

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or downtime costs. These costs are expressed in terms of either annual average losses (AAL), or mean exceedance probability (MEP) curves, which are graphical representations of the loss tail distributions.

This paper focuses on earthquake risk, and earthquake CRE analyses rely on performance-based engineering, which assumes a good understanding and characterization of the seismic hazard and of the structural system analysed. Seismic performance of structures is expressed in terms of seismic fragility which represents the probability of a structure to enter a damage state for given intensity levels of the seismic ground motion. Two major drawbacks make an accurate CRE analysis difficult, i.e., the limited number of ground motion records available at a site in order to perform a probabilistic analysis of the structural response, and the computational effort required to perform detailed dynamic analyses for complex structures. Traditionally, the insufficient number of ground motion records is overcome by scaling existing ground motion records to common increasing intensity measures until the specified damage state is reached [2–5]. The difficulty of performing dynamic analyses for complex system is often resolved by the simplification of the dynamic system. Complex, non-linear system are seen as simple linear single-degree-of-freedom (SDOF) systems.

The current paper proposes a new framework for performing CRE analyses, which addresses both issues identified previously. First, the method uses simulated ground motion records and secondly, efficient, non-intrusive methods are used to perform dynamic analyses accurately. Significant progress has been done in research for developing methods to simulate ground motion records, by either using mathematical models calibrated to actual records [6–9], or by using seismological models [10,11]. Response statistics of the structural system are performed efficiently, by using stochastic reduced order models (SROM) [12–14]. Like Monte-Carlo simulations, SROM uses samples of the seismic ground motion. Unlike Monte-Carlo simulations, SROM selects only a small number of samples of the ground motion in an optimal way. The methodology proposed allows for the calculation of distributions of loss estimates rather than just the mean values, such as AAL and MEP curves, which cannot provide an integral picture of the risk assumed by the asset.

2. Catastrophe Risk Engineering (CRE) Framework

The CRE framework is composed of three main parts: (1) the seismic hazard, (2) the structural system model and response analysis, and (3) the estimation of the loss metrics to describe structural seismic performance. This paper proposes a new methodology for doing CRE analyses, which tackles several issues of the traditional CRE framework. The difference between the features of the traditional and the new CRE frameworks are summarised in Table 1. Details about each part of the framework and how each of the feature is relevant for the purpose of the methodology are presented in the following sub-sections.

Table 1. Description of CRE frameworks.

Feature	Traditional CRE Framework	New CRE Framework
Seismic input	Scaled real records	Simulated records
Intensity measure (IM)	Spectral acceleration, SA	Moment magnitude and source-to-site distance, (m, r)
Structural fragility	Fragility curves	Fragility surfaces
Methodology	Monte-Carlo simulations	Stochastic reduced order models
Link between seismic hazard and IM	Ground motion prediction equations	not needed

2.1. Seismic hazard

Seismic hazard is described by two elements, the statistics of earthquake activity at the site where the asset is located, and a model used for the simulation of site-specific ground-motion samples. The earthquake statistics at this site are given by the seismic activity matrix (SAM), which represents the probability of occurrence of earthquakes characterized by the magnitude m and the source-to-site distance r. The SAM is calculated with data provided by the USGS [15] for every site in the United States. For exemplification, a site in San Francisco is considered to be the location of the asset of interest, and the corresponding seismic activity matrix is shown in Figure 1 (left panel).

The model used for the seismic ground motion is presented in [14], and it is defined as a non-stationary, non-Gaussian, zero-mean stochastic process $A(t)$. The probability distribution of $A(t)$ is the Student's t distribution, with second-moment properties fully defined by the power spectral density function $g(\nu; m, r)$, with argument the frequency

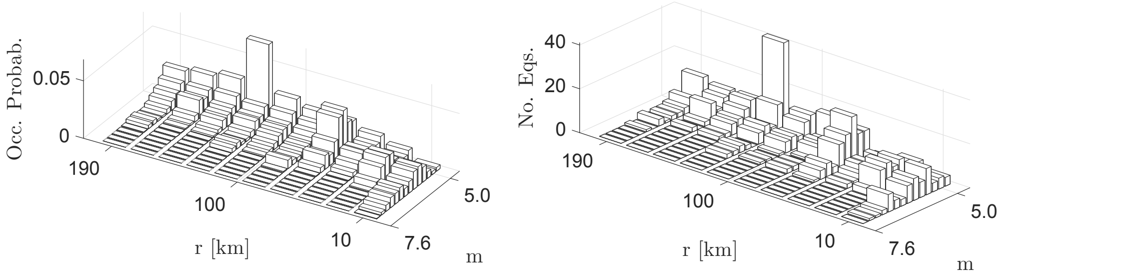

Fig. 1. Seismic activity matrix for San Francisco, zip code 94111 (left panel) and a sample of the life-cycle number of events for each (m, r) (right panel).

ν and parameters the moment magnitude m and the source-to-site distance r. Function $g(\nu; m, r)$ is an output of the specific barrier model [16], statistically updated to site-specific records in [11]. the further two moments, i.e., the skewness and the kurtosis of the distribution for $A(t)$, are calibrated to the mean values obtained from USGS data, and are 0 and 5.67, respectively.

Figure 2 shows the spectral density function $g(\nu; m = 7, r = 50\ km)$ and a sample of the corresponding ground motion. Details about the calibration of the spectral density function to site records and the simulation of ground motion samples using the spectral representation method and non-Gaussian memoryless transformations are given in the reference papers [11,14].

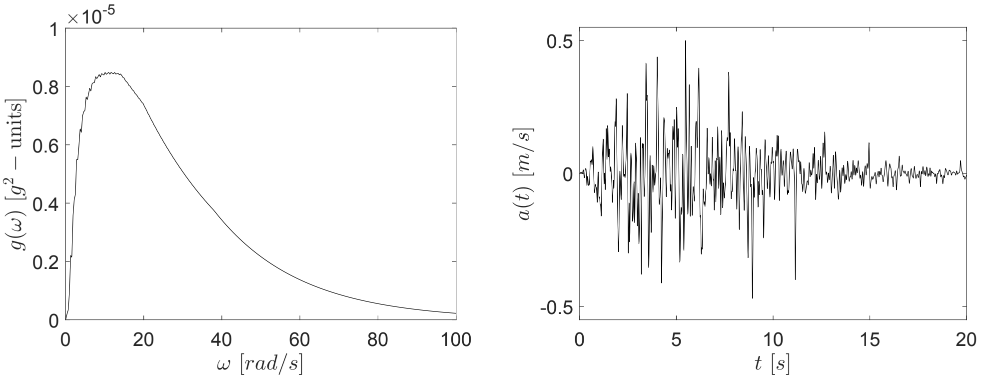

Fig. 2. Power spectral density (left panel) and sample of ground motion (right panel) for magnitude $m = 7$, and source-to-site distance of $r = 50\ km$.

The model for the ground motion simulation can be used to generate any number N of ground motion samples, and the ground motion model can be substituted by any other model that can simulate ground motion samples as a function of (m, r).

2.2. Structural system and response analysis

Two simple SDOF oscillators, one linear described by Eq.(1), and one non-linear described by Eq.(2), also known as the Bouc-Wen oscillator, are used as structural systems to show how the framework works and its advantages.

$$\ddot{X}_{lin}(t) + 2\zeta_0\nu_0\dot{X}_{lin}(T) + \nu_0^2 X_{lin}(t) = -A(t) \tag{1}$$

$$\begin{aligned} &\ddot{X}_{bw}(t) + 2\zeta_0\nu_0\dot{X}_{bw}(T) + \nu_0^2(\rho X_{bw}(t) + (1-\rho)W(t)) = -A(t) \\ &\dot{W}(t) = \gamma\dot{X}_{bw}(t) - \alpha|\dot{X}_{bw}(t)||W(t)|^{\eta-1}W(t) - \beta\dot{X}_{bw}(t)|W(t)|^{\eta}, \end{aligned} \tag{2}$$

The displacement of the linear and non-linear Bouc-Wen oscillators are denoted by $X_{lin}(t)$ and $X_{bw}(t)$, respectively, and $A(t)$ is the stochastic process that describes the seismic input, and was defined in the previous section. Since the framework proposed is identical irrespective of the system considered, further on, in the description of the CRE framework, we will use the generic notation $X(t)$ for the response displacement of the system, where, in this case, $X(t)$ can be either $X_{lin}(t)$ or $X_{bw}(t)$. Parameters ζ_0 and ν_0 are known as the damping ratio and the natural frequency of the linear SDOF system, and coefficients $\rho,\ \alpha,\ \beta,\ \gamma$ and η are scalars defining the non-linear properties of the Bouc-Wen oscillator. The values of the parameters describing the two SDOF systems used for the numerical examples are $\zeta_0 = 2\%,\ \nu_0 = 2\pi\ rad/s,\ \alpha = 0.001, \beta = 2, \gamma = 4, \eta = 1, \rho = 0.15$. Note that for $\rho = 1$, the two oscillators are identical. In fact, in the context of the traditional CRE framework, the linear SDOF system can be regarded as a proxy for the Bouc-Wen oscillator.

It has been shown that the commonly-used spectral acceleration (SA) as an intensity measure for fragility curves is unsatisfactory for non-linear structures [17]. More recently, it has been inferred [18] that SA and the response of non-linear structures are weakly dependent and the resulting fragility in terms of SA have large uncertainties which limit their usefulness. Therefore a vector-valued intensity measure (m, r), in terms of the moment magnitude m and source-to-site distance r, which relate directly to the seismic hazard, is chosen for the current framework. The resulting fragility expressed as a function of (m, r) is called fragility surface and can be defined as:

$$P_s(m, r) = \mathbb{P}\{max_{t\geq 0}|X(t)| > x_{cr}|M = m, R = r\}, \tag{3}$$

where x_{cr} is a critical threshold for the displacement $X(t)$ of the system.

Figure 3 shows the fragility surfaces calculated for the linear (left panel) and the Bouc-Wen (central panel) systems, for $x_{cr} = 2\ cm$. The significant differences in the structural performance of the two systems is shown in terms of the proxy fragility curves calculated with data extracted from the corresponding fragility surfaces, shown in Figure 3 (right panel). Proxy fragility curves have been calculated as parametric log-normal cumulative distribution functions calibrated to data extracted from the fragility surface $P_c(\overline{SA|(M = m, R = r)}) = P_s(m, r)$, where $\overline{SA|(M = m, R = r)}$ is the median spectral acceleration calculated from ground motion prediction equations (GMPEs), for an event characterized by (m, r). The GMPE by Abrahamson and Silva in [19], was used for the purpose of this paper.

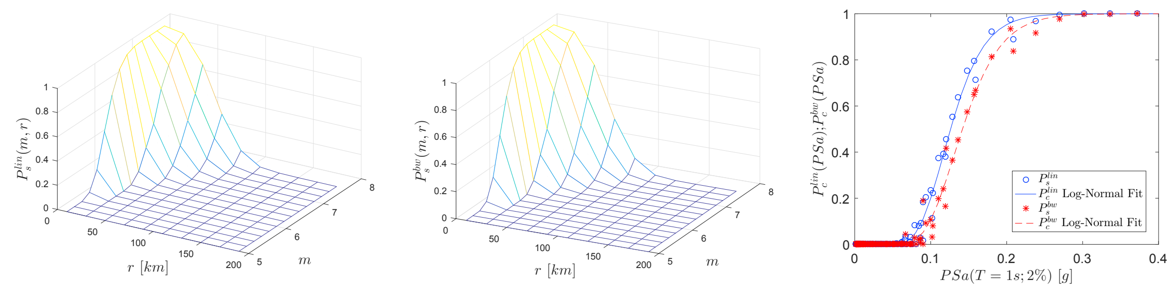

Fig. 3. Fragility surfaces for the linear SDOF system(left) and the Bouc-Wen SDOF oscillator (center) and proxy fragility curves for the linear and teh Bouc-Wen systems (right).

The only reliable method for calculating statistics of structural systems to seismic input is by Monte Carlo simulations, which is computationally expensive in case of complex non-linear structures, for large numbers N of ground motion samples. The calculation of fragility surfaces requires multiple dynamic analyses for each (m, r) in the SAM, and therefore SROMs for the process $A(t)$ for each (m, r) are sought. The fragility surfaces in this paper were calculated using SROMs and the reliability and the efficiency of the method are discussed in detail in [14].

A stochastic reduced order model $\tilde{A}(t)$ for $A(t)$ is a stochastic process with $\tilde{N}$ samples $\{a_i(t),\ i = 1, ..., \tilde{N}\}$ of $A(t)$ weighed by probabilities $\mathbf{p} = \{p_i \geq 0,\ i = 1, ..., \tilde{N}\}$ such that $\sum_{i=1}^{\tilde{N}} p_i = 1$. Pairs $\{a_i(t), p_i\}$ define completely the probability law of $\tilde{A}(t)$. To construct $\tilde{A}(t)$ we select sets of $\tilde{N}$ samples of $A(t)$ and select their corresponding probabilities $p_i,\ i = 1, ..., \tilde{N}$ such that the discrepancy between the probability laws of $A(t)$ and $\tilde{A}(t)$, defined by the differences between (1) the marginal distributions $\int_{-\infty}^{\infty}\int_0^{t_f}\left(\sum_{i=1}^{\tilde{N}} p_i \mathbb{1}\{a_i(t) \leq x\} - F(x, t)\right)^2 dtdx$, (2) the moments up to order q $\sum_{q=1}^{n_q}\int_0^{t_f}\left(\sum_{i=1}^{\tilde{N}} p_i a_i(t)^q - \mu(t; q)\right)^2 dt$, and (3) the correlation functions $\int_0^{t_f}\int_0^{t_f}\left(\sum_{i=1}^{\tilde{N}} p_i a_i(t)a_i(s) - c(t, s)\right)^2 dtds$, respectively. Functions $F(x, t)$, $\mu(t, q)$ and $c(t, s)$ are the marginal distribution, moments of order $q = 1, ..., n_q$ and correlation functions of $A(t)$, respectively, where n_q is the order of the highest moment considered.

The set of $\tilde{N}$ samples with $\mathbf{p} = \mathbf{p}^{\mathbf{opt}}$ which provides the minimum value for the metric $f(\mathbf{p}^{\mathbf{opt}})$ defines the SROM $\tilde{A}(t)$. The range of $\tilde{A}(t)$ is sub-optimal because we use a fixed, relatively small number of distinct sets of $\tilde{N}$ samples of $A(t)$ to select the samples for the SROM. Then the fragility surface defined in Eq.(3) can be re-written using the SROM samples for a given (m, r) as:

$$P_s(m, r) = \frac{1}{\tilde{N}} \sum_{i=1}^{\tilde{N}} p_i \mathbb{1}\{\max_{0 \le t \le t_f} |\tilde{x}_i(t)| > x_{cr}\}. \tag{4}$$

2.3. Loss estimates

Two metrics are used in CRE to quantify the seismic performance of structures, the annual average loss (AAL) and the mean exceedance probability (MEP) curve of losses. In order to perform this calculation, the following simplifying assumptions are made:

- the replacement value of each of the assets, i.e., the value of the asset at the time of the event, is $V = 1$;
- the asset is assumed to be undamaged, i.e., with value $V = 1$, before each event;
- the ratio between the cost of the repair of a structure subjected to an earthquake characterized by (m, r) and the replacement value is given by $P_s(m, r)$.

The stated assumptions are not restrictive and are consistent with the catastrophe-modelling industry. However, a regenerative process can be used to account for damage and repairs after each event as shown in [14].

Under the simplifying assumptions, the loss for a given event (m, r) is calculated as $L = VP_s(m, r)$. In order to calculate the probability distribution for event losses L, a life-cycle analysis must be performed. A life-time of $\tau = 1,000$ *yrs* is assumed and a mean annual rate of occurrence $\lambda = 0.521$ for earthquakes of magnitude $m > 5$ within a distance of 200 *km* from the asset is calculated from USGS [15]. Under the assumption that the number of earthquakes $N(\tau)$ that occur in τ years is a Poisson process with intensity λ, earthquakes events with parameters (m, r) are generated according to the distribution of events given by the SAM shown in Figure 1 (left panel). A sample of the number of events for each (m, r) for the period τ is shown in Figure 1 (right panel).

The tail distribution of the event losses L is calculated by:

$$\mathbb{P}(L > l) = \frac{1}{N(\tau)} \sum_{k=1}^{N(\tau)} \mathbb{1}(l_k > l), \tag{5}$$

where $l_k = VP_s(m_k, r_k)$ is the loss for event (m_k, r_k), $k = 1, ..., N(\tau)$ and $\mathbb{1}$ is the indicator function. The graphic representation of $\mathbb{P}(L > l)$ is known as the exceedance probability (EP) curve. A number of $N_s = 1,000$ life-cycle scenarios are simulated and the EP curves calculated for each scenario are shown in Figure 4 (left panel). The mean exceedance probability (MEP) curve calculated as the average of the EP curves for all N_s scenarios, the 5^{th} and the 95^{th} percentiles EP curves are also indicated in Figure 4 (left panel).

If we assume that the linear system had been used as a proxy for the Bouc-Wen oscillator in the traditional CRE framework, then Figure 4 (right panel) shows a comparison between the EP curves obtained through the two frameworks. The Bouc-Wen systems (solid lines) have been calculated using the proposed framework, while the EP curves for the linear system have been calculated using the proxy fragility curve shown in Figure 3 (right panel). The differences are significant and the confidence intervals defined by the 5^{th} and the 95^{th} percentiles are almost disjoint for lower losses.

3. Conclusions

A novel framework for earthquake catastrophe risk engineering analyses is proposed in order to quantify accurately seismic risk of structures. The new methodology uses simulated site-specific ground motion records to perform dynamic analyses of the structures analysed. Seismic fragility of structures is expressed as functions of moment magnitude and source-to-site distance, calculated efficiently using stochastic reduced order models. Probability distribution of life-cycle cost estimates are produced, and significant differences in the losses calculated with the traditional and the newly proposed CRE frameworks are observed.

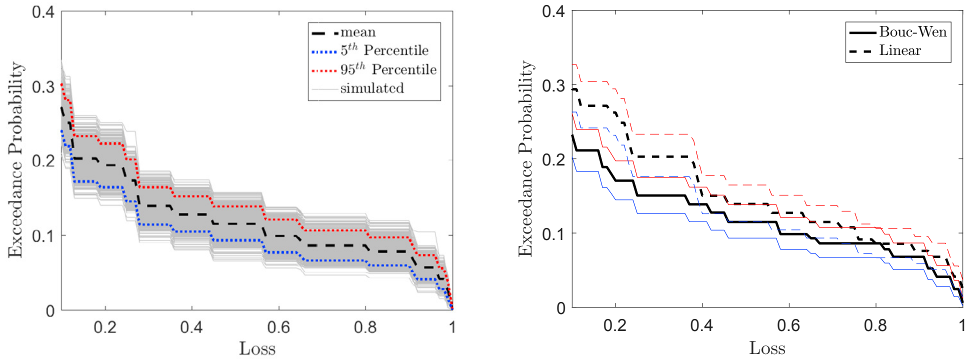

Fig. 4. EP curves for the Bouc-Wen oscillator using fragility surfaces (left) and EP-curves comparison between the linear and the Bouc-Wen oscillators (right).

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